
Modeling of Hysteretic Behavior of Shape Memory Alloys Using a Rate-Independent Phase-Field Framework

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Abstract

Shape memory alloys (SMAs) are a prominent class of multifunctional materials with remarkable thermomechanical properties, offering significant potential for engineering applications. Their behavior is characterized by stress- and temperature-induced phase transformations between austenite and multi-variant martensite, enabling unique functionalities such as superelasticity and shape recovery. These transformations are accompanied by energy dissipation, which is the origin of hysteretic behavior under cyclic thermo-mechanical loading. Experiments reveal that the majority of SMAs exhibit rate-independent responses under quasi-static conditions, maintaining finite-width hysteresis loops even at extremely low loading rates. The phase-field method has emerged as a powerful modeling framework for capturing the evolution of complex interface topologies in SMAs. Despite numerous important contributions addressing the continuum mechanical description of SMAs, see (1) and the references therein, most existing models employ rate-dependent dissipation formulations, limiting their ability to replicate the thermo-elastic hysteresis loops with finite width, as observed in experiments under quasi-static conditions.

To address this gap, this study extends a thermomechanically coupled and variationally consistent phase-field approach that integrates both rate-dependent and rate-independent driving force formulations, as detailed in (2). Additionally, it incorporates temperature dependent local energetic minima within the free energy landscape to accurately model sigmoidal undercooling hysteresis as welll as stress- and temperature-induced martensite pattern formation. Two-dimensional finite element simulations demonstrate the applicability of the proposed framework in analyzing microstructure evolution in twinned martensite, remanent microstructure formation under cyclic loading, as well as hysteresis behavior. These studies involve the influence of driving force related thresholds and the calibration of model parameters using experimentally observed martensite start and finish temperatures. Moreover, the introduction of nonlinearly weighted averaging operators further enhances the macroscopic characterization of microstructural features (see (3)). Future extensions of the framework to multi-phase and multi-variant alloy systems are also outlined, underscoring its applicability.

References:

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